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EMPIRICAL COMPARISON OF A FIXED-BASE  
AND A MOVING-BASE SIMULATION  
OF A HELICOPTER ENGAGED IN  
VISUALLY CONDUCTED SLALOM RUNS

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# EMPIRICAL COMPARISON OF A FIXED-BASE AND A MOVING-BASE SIMULATION OF A HELICOPTER ENGAGED IN VISUALLY CONDUCTED SLALOM RUNS

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## SUMMARY

An evaluation study has been completed of combined visual, motion, and aural cues for a helicopter engaged in visually conducted slalom runs at low altitude. The evaluation of the visual and aural cues was subjective, whereas the motion cues were evaluated both subjectively and objectively. Subjective opinion and objective data conflicted in the detection of differences in the performance of a primary and secondary task under motion and no motion conditions. Subjectively, differences in performance were expected, and objectively, no significant differences were detected. However, subjective and objective results coincided in the area of control activity. Generally, less control activity is present under motion conditions than under fixed-base conditions, a fact attributed subjectively to the feeling of realistic limitations of a machine (helicopter) given by the addition of motion cues. The objective data also revealed that the slalom runs were conducted at significantly higher altitudes under motion conditions than under fixed-base conditions.

## INTRODUCTION

Some of the factors affecting the quality of a flight simulator are the mathematical model of the flight vehicle, the cockpit hardware (control system, instrumentation, etc.) and the visual, motion, and aural cues provided to the pilot. The final three factors are thought to be of considerable importance in the simulation of a helicopter, particularly when low-altitude maneuvering is simulated.

The importance of visual cues to the helicopter pilot is well understood (ref. 1), although disagreement exists as to the exact nature of the visual requirements for simulation. The addition of motion cues seems intuitively important in a vehicle possessed with the capabilities of rapid movement within three-dimensional space. Aural cues should also be significant in providing the pilot with information relative to his vehicle's performance.

The recent acquisition of a modern terrain board display system, to be used with the virtual image "out-the-window" display monitor available in the Langley visual-motion simulator (VMS), allowed for an evaluation study of combined visual, motion, and aural cues for a helicopter engaged in visually conducted slalom runs at low altitude. The study utilized a rigorously validated fixed-base

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simulation of an S-61 helicopter that was modified to allow for the inclusion of the visual, motion, and aural cues to be evaluated.

This paper will present the subjective and objective data collected during fixed-base and moving-base operation of the simulator during the visually conducted slalom runs, the main emphasis being placed on the comparison of the objective data under fixed-base and motion-base operation.

## SYMBOLS

Measurements and calculations were made in U.S. Customary Units. They are presented herein in the International System of Units (SI) with the equivalent values given parenthetically in the U.S. Customary Units.

A,B,C	main effects in analysis of variance
AB,AC,BC	two-factor interactions in analysis of variance
ABC	three-factor interaction in analysis of variance
$a_x, a_y$	body-axis longitudinal and lateral acceleration at centroid location, $m/sec^2$ (ft/sec <sup>2</sup> )
$a_z$	body-axis vertical acceleration (referenced about 1g) at centroid location, $m/sec^2$ (ft/sec <sup>2</sup> )
$b_x, b_y, b_z$	coefficients for position penalties in cost functions, per sec <sup>4</sup>
$b_\psi$	coefficient for yaw-position penalty in cost function, per sec <sup>2</sup>
$\dot{c}$	collective stick rate, m/sec (ft/sec)
$c_x, c_y, c_z$	coefficients for velocity penalties in cost functions, per sec <sup>2</sup>
$d_x, d_y, d_z$	damping parameters for second-order translational washouts, per sec
$e_x, e_y, e_z$	frequency parameters for second-order translational washouts, per sec <sup>2</sup>
$e_\psi$	parameter for first-order yaw washout, per sec
$F_{DB}$	deadband on pedal force signal, V
$F_p$	transducer signal for pilot force on pedals, V
$F_{\delta,p}$	pedal force feedback signal, V
$f_{i,x}, f_{i,y}$	inertial-axis translational acceleration commands prior to translational washout, $m/sec^2$ (ft/sec <sup>2</sup> )
$f_{s,x}, f_{s,y}$	body-axis translational accelerations, $m/sec^2$ (ft/sec <sup>2</sup> )

$g$	gravitational constant, $m/sec^2$ ( $ft/sec^2$ )
$h$	altitude, $m$ ( $ft$ )
$K_{c,1}, K_{c,2}, K_{c,3},$ $K_{c,4}, K_{c,5}, K_{c,6}$	coefficients for initial-condition penalties in cost functions, per sec
$K_{x,1}, K_{y,1},$ $K_{x,3}, K_{y,3}$	$K_z$ gain parameters, $sec^3/m^2$ ( $sec^3/ft^2$ )
$K_{x,2}, K_{y,2}$	gain parameters, $sec^5/m^4$ ( $sec^5/ft^4$ )
$K_\psi$	yaw gain parameter, sec
$p_a, q_a, r_a$	body-axis aircraft angular velocities, rad/sec
$p_{x,1}, p_{x,3},$ $p_{y,1}, p_{y,3}$	$p_z$ adaptive parameters, position limited
$p_{x,2}, p_{y,2}$	adaptive parameters, position limited, $sec/m$ ( $sec/ft$ )
$p'_{x,1}, p'_{y,1},$ $p'_{x,3}, p'_{y,3}$	$p'_z$ adaptive parameters, rate limited
$p'_{x,1}(0), p'_{y,1}(0),$ $p'_{x,3}(0), p'_{y,3}(0)$	$p'_z(0)$ initial conditions on adaptive parameters, rate limited
$p'_{x,2}, p'_{y,2}$	adaptive parameters, rate limited, $sec/m$ ( $sec/ft$ )
$\ddot{p}_{x,1}, \ddot{p}_{y,1},$ $\ddot{p}_{x,3}, \ddot{p}_{y,3}$	$\ddot{p}_z$ adaptive-parameter rates, per sec
$\ddot{p}_{x,2}, \ddot{p}_{y,2}$	adaptive-parameter rates, per $m$ (per $ft$ )
$p_\psi$	adaptive yaw parameter, position limited
$p'_\psi$	adaptive yaw parameter, rate limited
$p'_\psi(0)$	initial condition on adaptive yaw parameter, rate limited
$\ddot{p}_\psi$	adaptive-yaw-parameter rate, per sec
$R$	pedal-centering signal, $V$
$\Delta R$	pedal-position error signal, $V$

RPM	revolutions per minute of rotor
$S_x, S_y$	scale factors on body-axis translational accelerations
$u$	longitudinal body-axis velocity, knots
$V$	true airspeed, knots
$W_x, W_y$	angular-rate weighting coefficients, $m^2/sec^2$ ( $ft^2/sec^2$ )
$x, y, z$	commanded inertial translational position of motion simulator, m (ft)
$\delta_c$	collective position, m (ft)
$\delta_p$	pedal position signal, V
$\delta_{p,c}$	commanded pedal position, V
$\theta_a$	actual aircraft pitch angle, deg
$\phi_a$	actual aircraft roll angle, deg
$\psi, \theta, \phi$	commanded inertial angular position of motion simulator, rad
$\psi_a$	actual aircraft heading, deg
$\dot{\psi}_a, \dot{\theta}_a, \dot{\phi}_a$	aircraft angular velocities, rad/sec
$\omega_n$	aural-cue pulse frequency, rad/sec
$\omega_p$	a past iteration value of aural-cue pulse frequency, rad/sec

Dots over symbols denote derivatives with respect to time.

## SIMULATOR DESCRIPTION

The simulator was assembled with the elements: mathematical model, visual system, motion system, simulator cockpit, and aural cueing.

### Mathematical Model

A rigorously validated six-degree-of-freedom total force and moment mathematical model of a helicopter, including a modified blade element rotor model, was used in the study. It was actually a modified model of a Huey-Cobra helicopter with a stability augmentation system tuned so that the handling characteristics of the S-61 helicopter are closely duplicated. The development of the program of the helicopter model is documented in reference 2, and the first application of the model is documented in reference 3.

## Visual System

The visual system consists of a state-of-the-art TV-camera transport system used in conjunction with a sophisticated terrain model board. (See fig. 1.) The model board, 7.32 m (24 ft) by 18.3 m (60 ft), offers terrain at a 750/1 scale and a 1500/1 scale. A slalom course consisting of 45.72-m (150 ft) trees placed about 426.72 m (1400 ft) apart on alternating sides of a river bank was laid out on part of the 1500/1 scale model. The measured course was about 9.26 km (5 n. mi.) long and consisted of 17 trees. Two extra trees were utilized before the measured course began to stabilize initial performance.

The approximate second-order transfer function parameters for the camera transport system are presented in reference 4, and show translational lags of 50 msec or less and rotational lags of 75 msec or less. The "out-the-window" virtual image system, located nominally 1.27 m (4.17 ft) from the pilot's eye, presented a nominal  $48^\circ$  width by  $36^\circ$  height field of view of a 525 TV line raster system and provided a  $46^\circ$  by  $26^\circ$  instantaneous field of view. The system supplies a color picture of unity magnification with a nominal resolution on the order of 9 minutes of arc.

## Motion System

The Langley visual-motion simulator (VMS, fig. 2) is a six-degree-of-freedom synergistic motion base with performance limits as listed in table I. References 5, 6, and 7 document the characteristics of the system, which possesses time lags (around 50 msec) that are very close to those of the visual system. The washout system used to present the motion-cue commands to the motion base is nonstandard. It was conceived and developed at Langley Research Center and it is documented in references 8 and 9. The basis of the washout is the continuous adaptive change of parameters to minimize a cost functional through continuous steepest descent methods, and to produce the motion cues in translational accelerations and rotational rates within the motion envelope of the synergistic base. The specific parameters of the nonlinear coordinated adaptive washout used in this helicopter study are presented in table II. Figure 3 presents a block diagram of the washout system and the appendix presents the equations. It should be noted that the heave cue supplied to the pilot was based only on the rate of change of collective stick position rather than on normal acceleration. This arrangement allowed for significant heave-cue introduction without the phasing and amplitude problems that arise when trying to present the cue based on normal acceleration. Simulation of vibration, obtained from the aural-cue drives, was also presented in the vertical motion channel.

## Simulator Cockpit

The general-purpose transport cockpit of the VMS was modified to represent a helicopter by installing a two-axis side-arm controller to supply cyclic inputs. The cyclic controller was loaded with springs and dash pots. The rudder pedals were loaded by a hydraulic system coupled with a special-purpose analog computer. However, to simulate the "free-floating" rudder pedals of a helicopter, it was necessary to augment the control loader with the digital

simulation computer, as shown in figure 4. With this system, the rudder pedals remain in the position at which the foot force was removed rather than return to the center position. The collective stick in the VMS is a counter-balanced, friction-controlled stick, and it is representative of a helicopter collective.

Primary instrumentation consisted of an attitude indicator, vertical speed indicator, an altimeter, an RPM indicator, a turn and bank indicator, a compass card, and an airspeed indicator. The airspeed indicator was driven with  $V$  when  $V$  was above 20 knots, and with  $+u$  when  $V$  was below 20 knots. A 17.78-cm-diameter (7 in.) cathode ray tube was mounted on top of the instrument panel, at a  $40^\circ$  angle to the pilot's look axis, to enable the presentation of a secondary visual task that would be independent of the primary visual scene.

### Aural Cueing

A sine wave of 100 Hz was multiplied on a general-purpose analog computer with a half-rectified sine wave of controlled amplitude and frequency generated on the digital computer to provide the aural cues to the simulator. The 100-Hz sine wave provided a realistic tone, the half-rectifying of the second sine wave provided the pulsing desired, and amplitude and frequency variations of the second sine wave provided the rotor loading cues desired. The empirical equations for the control of amplitude and frequency of the second sine wave used within the digital computer were

$$\begin{aligned} \text{Amplitude} = & 0.203 \times |\theta_a + 0.13| + 0.002 \times |\text{RPM} - 290| + 0.00002 \times |\dot{h}| \\ & + 0.15 \times |\phi_a| + 0.317\delta_c \end{aligned}$$

$$\text{Frequency} = \omega_p$$

$$\omega_p = \begin{cases} \omega_p & (|\omega_n - \omega_p| \leq 0.1) \\ \omega_n & (|\omega_n - \omega_p| > 0.1) \end{cases}$$

$$\omega_n = 0.1112 \times \text{RPM}$$

The half-rectified sine wave was also introduced into the heave channel of the motion base to simulate vibration levels.

### PARTICIPATING PILOTS AND TASKS

Four research pilots and three research engineers with extensive experience in flight simulators participated in this study. Because of the extensive learning curves associated with both the primary task and the secondary task, the large number of data flights, and the various schedule interruptions that occurred, only one of the four research pilots completed a full set of data

runs. Thus, objective data results are available from only four subjects, although subjective comments are reported from the seven subjects.

### Primary Task

Each pilot was instructed to fly the slalom course with three goals:

- (1) Minimize the ground track deviation from an imaginary straight line drawn between the trees. A root-mean-square score for this deviation (calculated 32 times per sec) was measured and used in a primary task measure. The pilot was instructed to ignore tree-rotor distances due to lack of rotor visual representation and to approach each tree as closely as possible without hitting it.
- (2) Two hundred and ten sec was the allotted time to complete the course; this time required an average airspeed of 70 knots. The primary task measure penalized slower completion times and rewarded faster completion times. However, the pilot goal was to use exactly 210 sec.
- (3) Maintain an altitude of about 22.86 m (75 ft) above the ground level or midtree height.

### Secondary Task

Discrimination between fixed-base and moving-base operation is often enhanced by increased pilot workload (ref. 10). To increase the workload on the pilot, a visual secondary task was provided. An Adage graphics computer was programmed to present a random series of five digit numbers which were displayed on a 17.78-cm-diameter (7 in.) cathode ray tube offset from the pilot's look axis. The secondary task was to add the first, third, and fifth digit of each number and report the answer orally. The number was changed after each answer, and the number of correct answers recorded for each flight.

### Measures

Scores for the primary and secondary tasks were constructed as follows:

Primary task score - The root-mean-square deviation in ground track in m (ft) was multiplied by the time used to complete the course and divided by 210 sec.

Secondary task score - The number of correct answers given during the course was divided by the time used to complete the course.

Additional measures - A root-mean-square measure of pressure altitude was recorded for each flight although various positions of the river on the model were either above or below sea level (a radar altitude measure was not available). In addition to the root-mean-square value of altitude, eight other root-mean-square values were determined for all control input positions and rates; these values included cyclic pitch stick position and rate, cyclic roll stick position and rate, tail rotor pedal position and rate, and collective stick position and rate.

### TRAINING PROGRAM

The training procedure consisted of flying the course in both fixed-base and moving-base conditions without the secondary task until the primary task scores began to asymptote. The subjects were provided their scores after each

course run. To maintain subject motivation, the subjects were also informed of the other subjects' scores. The secondary task was then added and training continued until both the primary task and secondary task scores appeared to reach asymptotic levels.

During training it was noted that pilot performance deteriorated after about 15 successive course runs, the deterioration being attributed to the high work level involved in both tasks, and rest periods did little to revive sustained performance. As a result, it was decided that data collection would be limited to 10 runs per pilot per day and 5 practice runs prior to data collection.

### EXPERIMENTAL DESIGN

A  $2 \times 4^2$  full factorial design was utilized in this study. The motion factor was at two levels (fixed and moving base), and the pilot and the day factors at four levels each, with five replicates. This design gave a total of 160 data points, or 40 course runs per pilot. Motion conditions were randomized for each pilot each day and consisted of five with and five without motion.

Analyses of variance were carried out on each of the 11 separate measures to provide the objective data analysis. Subjective comments were collected throughout the training and data collection stages.

### EXPERIMENTAL RESULTS

Figure 5 displays a typical course run in terms of ground track and air-speed and altitude along the ground track. The x's symbolize tree positions along the measured course.

#### Objective Data Results

Because of the extensive amount of data involved in this study, data are presented only in forms necessary to illustrate the results. The summary of the results from the 11 analyses of variance is presented in table III, a single asterisk representing significance at the 5-percent level and a double asterisk denoting significance at the 1-percent level.

Single factor effects.— Although the main concern of this analysis is the motion factor, the other factors are of some interest.

Days (designated by A): In all 11 measures, the day factor was highly significant, and indicated that despite extensive training and the appearance of asymptotic behavior in performance scores, pilots collectively flew differently each day. A further breakdown of the data indicated that the pilots were in reality still on a learning curve.

Pilots (designated by B): In all 11 measures, the pilot variation was highly significant, each pilot flying differently.

Motion (designated by C): Although the motion factor was not significant in the primary and secondary task scores, it was highly significant in the control input measures, with the exception of cyclic roll. Further analysis revealed both root-mean-square position and rate values to be consistently lower under motion conditions than under fixed-base conditions, as depicted by the downward-pointing arrows in table III. Collective rate was higher for motion conditions for two subjects and lower for motion conditions for the other two subjects, as depicted by the double-headed arrow. Figure 6 is a typical illustration of motion-significant control activities. The root mean square of altitude was highly significant, pilots collectively flying higher (about 4 percent) under motion conditions than under fixed-base conditions, as depicted by the upward-pointing arrow. Further analysis revealed that each pilot flew higher with motion, and even though the magnitudes of mean differences were small between fixed-base and motion values, the differences were highly significant statistically.

Replicates: The secondary task score analysis showed replicates to be highly significant, and indeed a learning curve is evident in the data as shown in figure 7. Replicates were also found to be significant in pedal position and rate, and cyclic pitch rate. The data indicate peak activity typically during the second replicate and may be interpreted as either a learning curve or possibly an indication of the tiring of the pilot (fig. 8).

Interactions.— The significant interactions are examined by grouping the performance measures in terms of the number of significant interactions.

Measures with one significant interaction, AB: For the primary task score, altitude, and cyclic pitch rate, the pilot-days interaction AB was the only significant interaction; thus, the differences between pilots in these measures varied from day to day.

Measures with two significant interactions, AB and AC: For the secondary task score, the pilots-days interaction AB is also highly significant; again, the differences between pilots varied from day to day. The days-motion interaction AC is also significant for this measure, and indicates that the motion effect varied from day to day. As shown in figure 9, on days 1 and 4, average performance of the secondary task was higher with motion than without motion, whereas the order reversed on days 2 and 3. However, as the motion factor was not significant, the differences between performance levels of the secondary task were not consistently significant.

Measures with two significant interactions, AB and BC: In addition to the pilot-days interaction AB, the pilot-motion interaction BC was highly significant for cyclic roll position and rate, cyclic pitch position, and pedal rate. Thus, the motion effect is indicated to be larger for some pilots than for others. Indeed, for those measures with no significant motion factor (roll position and rate), some pilots used more control with motion, whereas others used more control under fixed-base conditions. However, these differences in control levels were not consistently significant.

Measures with three significant interactions, AB, BC, and ABC: For collective position and rate, and pedal position, the days-pilots AB and pilots-

motion BC interactions are highly significant, and indicated that pilot differences varied from day to day, and that the differences between the higher control levels under fixed-base operation and the lower control levels with motion varied from pilot to pilot. As mentioned previously, although the differences under motion conditions for collective rate levels were highly significant, the levels for two pilots were higher for motion operation than for fixed-base operation. However, these pilots did not use the collective stick very much. (See fig. 10.) The three factor interaction, days-pilots-motion ABC, is also significant for these performance measures, and indicated that the days-pilots AB interaction varied under motion conditions C; that is, the pilot differences which varied from day to day were different under the motion conditions.

Summary of objective data results.- Although no significant differences under motion conditions were found for either the primary task or the secondary task, most control activity, both rate of change and magnitude, was lower under moving-base conditions than under fixed-base conditions. The root-mean-square altitude was higher with motion.

### Subjective Data Results

Motion cues.- All seven subjects thought the motion cues were extremely realistic, including the vibration introduced into the heave channel from the aural circuit. Vibrational changes with pitch angle, bank angle, sink rate, collective position, and RPM were felt to be very representative of rotor-loading situations. The subjects assessed the motion effect on performance to be one that constrained violent inputs. When flying under fixed-base conditions, there was no feeling of the physical limitations of a machine (helicopter), and thus control inputs could be utilized that under moving-base conditions present a feeling of strain on the aircraft. Thus, surprise was expressed by all pilots in the fact that fixed-base performance was not superior to moving-base performance in the primary task. (See fig. 11.) Superior performance was also expected, but not obtained (fig. 10), by the subjects with the secondary task under moving-base conditions, as they felt more comfortable in leaving the window scene to pick up the secondary display with the alerting motion cues present.

Visual cues.- All seven pilots expressed extreme satisfaction with the visual scene, although a larger field of view was thought to be desirable for the slalom task, especially in the vertical field. Earlier visual acquisition of the next tree would then have been possible. After rounding a tree, a nosedown attitude to increase speed was a typical maneuver; this maneuver often involved loss of sight of the next tree. This overall satisfaction with the visual scene was a pleasant surprise, because the terrain model board was not manufactured with low-altitude realism as a goal other than in runway areas. No problems were experienced with the focus control of the visual system, as the desired objects to be viewed, both near and far, were sufficiently clear to eliminate pilot dissatisfaction.

Aural cues.- Loss of the aural cues, which occurred during some of the training due to schedule conflicts for the analog computer, was viewed as highly objectionable by the pilots. Many felt the aural cues to be as important as the motion cues in adding realism. Variations with pitch angle, bank angle, sink

rate, collective stick position, and RPM were felt to be both helpful and realistic.

#### CONCLUDING REMARKS

The pilots felt that the S-61 helicopter simulation with visual, motion, and aural cues approached the real-world situation better than any simulator in their experience, particularly since it flew like a helicopter, a fact attributable to the mathematical model, as well as to the visual, motion, and aural cues. Although subjective opinion conflicted with objective data in the performance of the primary and secondary tasks under the motion conditions (in that no significant differences were detected between fixed base and motion), the lessened control activity with motion was significantly different from the activity without motion. The significant difference detected in control activity was subjectively attributed to the feeling of realistic limitations of a machine given by the addition of motion cues. The significant difference detected in altitude was subjectively attributed to this feeling of realistic limitations of a machine although this was not as direct as that for lessened control activity under motion conditions.

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# APPENDIX

## COORDINATED ADAPTIVE WASHOUT

The following equations are those of the nonlinear washout and correspond to figure 4. The derivation of these equations may be found in reference 5.

Longitudinal filter equations:

$$\ddot{x} = p_{x,1} f_{i,x} - d_x \dot{x} - e_x x$$

$$\dot{\theta} = p_{x,2} f_{i,x} + p_{x,3} \dot{\theta}_a$$

$$\dot{p}_{x,1}'' = K_{x,1} \left[ (f_{i,x} - \ddot{x}) \frac{\partial \ddot{x}}{\partial p_{x,1}} - b_x x \frac{\partial x}{\partial p_{x,1}} - c_x \dot{x} \frac{\partial \dot{x}}{\partial p_{x,1}} \right] + [p_{x,1}'(0) - p_{x,1}] K_{c,1}$$

$$\dot{p}_{x,1}' = \begin{cases} \dot{p}_{x,1}'' & (\dot{p}_{x,1}'' > -0.06) \\ -0.06 & (\dot{p}_{x,1}'' \leq -0.06) \end{cases}$$

$$p_{x,1} = \begin{cases} 1 & (p_{x,1}' > 1) \\ p_{x,1}' & (-0.1 \leq p_{x,1}' \leq 1) \\ -0.1 & (p_{x,1}' < -0.1) \end{cases}$$

$$\dot{p}_{x,2}'' = K_{x,2} \left[ (f_{i,x} - \ddot{x}) \left( \frac{\partial \ddot{x}}{\partial p_{x,2}} - \frac{\partial f_{i,x}}{\partial p_{x,2}} \right) + w_x (\dot{\theta}_a - \dot{\theta}) \frac{\partial \dot{\theta}}{\partial p_{x,2}} - b_x x \frac{\partial x}{\partial p_{x,2}} - c_x \dot{x} \frac{\partial \dot{x}}{\partial p_{x,2}} \right]$$

$$\dot{p}_{x,2}' = \begin{cases} 0.01 & (\dot{p}_{x,2}'' > 0.01) \\ \dot{p}_{x,2}'' & (-0.01 \leq \dot{p}_{x,2}'' \leq 0.01) \\ -0.01 & (\dot{p}_{x,2}'' < -0.01) \end{cases}$$

$$p_{x,2} = \begin{cases} 0.05 & (p_{x,2}' > 0.05) \\ p_{x,2}' & (0.01 \leq p_{x,2}' \leq 0.05) \\ 0.01 & (p_{x,2}' < 0.01) \end{cases}$$

$$\begin{aligned} \ddot{p}_{x,3} = K_{x,3} & \left[ (f_{i,x} - \ddot{x}) \left( \frac{\dot{\ddot{x}}}{\partial p_{x,3}} - \frac{\partial f_{i,x}}{\partial p_{x,3}} \right) + w_x (\dot{\theta}_a - \dot{\theta}) \frac{\partial \dot{\theta}}{\partial p_{x,3}} - b_x x \frac{\partial x}{\partial p_{x,3}} \right. \\ & \left. - c_x \dot{x} \frac{\partial \dot{x}}{\partial p_{x,3}} \right] + [p_{x,3}''(0) - p_{x,3}] K_{c,2} \end{aligned}$$

$$p_{x,3} = \begin{cases} 1 & (p_{x,3}'' > 1) \\ p_{x,3}'' & (0 \leq p_{x,3}'' \leq 1) \\ 0 & (p_{x,3}'' < 0) \end{cases}$$

$$\left( \frac{\dot{\ddot{x}}}{\partial p_{x,1}} \right) = f_{i,x} - d_x \left( \frac{\dot{x}}{\partial p_{x,1}} \right) - e_x \left( \frac{\partial x}{\partial p_{x,1}} \right)$$

$$\left( \frac{\dot{\ddot{x}}}{\partial p_{x,2}} \right) = p_{x,1} \frac{\partial f_{i,x}}{\partial p_{x,2}} - d_x \left( \frac{\dot{x}}{\partial p_{x,2}} \right) - e_x \left( \frac{\partial x}{\partial p_{x,2}} \right)$$

$$\left( \frac{\ddot{x}}{\partial p_{x,3}} \right) = p_{x,1} \frac{\partial f_{i,x}}{\partial p_{x,3}} - d_x \left( \frac{\dot{x}}{\partial p_{x,3}} \right) - e_x \left( \frac{\partial x}{\partial p_{x,3}} \right)$$

$$\left( \frac{\dot{\partial \theta}}{\partial p_{x,2}} \right) = f_{i,x} + p_{x,2} \frac{\partial f_{i,x}}{\partial p_{x,2}}$$

$$\left( \frac{\dot{\partial \theta}}{\partial p_{x,3}} \right) = p_{x,2} \frac{\partial f_{i,x}}{\partial p_{x,3}} + \dot{\theta}_a$$

$$\begin{aligned} \frac{\partial f_{i,x}}{\partial p_{x,2}} = & [-f_{s,x}(\sin \theta \cos \psi) + f_{s,y}(\sin \phi \cos \theta \cos \psi) \\ & - g(\cos \phi \cos \theta \cos \psi)] \frac{\partial \theta}{\partial p_{x,2}} \end{aligned}$$

$$\begin{aligned} \frac{\partial f_{i,x}}{\partial p_{x,3}} = & [-f_{s,x}(\sin \theta \cos \psi) + f_{s,y}(\sin \phi \cos \theta \cos \psi) \\ & - g(\cos \phi \cos \theta \cos \psi)] \frac{\partial \theta}{\partial p_{x,3}} \end{aligned}$$

$$\begin{aligned} f_{i,x} = & S_x f_{s,x}(\cos \theta \cos \psi) + S_y f_{s,y}(\sin \phi \sin \theta \cos \psi - \cos \phi \sin \psi) \\ & - g(\cos \phi \sin \theta \cos \psi + \sin \phi \sin \psi) \end{aligned}$$

Lateral filter equations:

$$\ddot{y} = p_{y,1} f_{i,y} - d_y \dot{y} - e_y y$$

$$\dot{\phi} = -p_{y,2} f_{i,y} + p_{y,3} \dot{\phi}_a$$

$$\dot{p}_{y,1}'' = K_{y,1} \left[ (f_{i,y} - \ddot{y}) \frac{\partial \ddot{y}}{\partial p_{y,1}} - b_{y,y} \frac{\partial y}{\partial p_{y,1}} - c_y \dot{y} \frac{\partial \dot{y}}{\partial p_{y,1}} \right] + [p_{y,1}'(0) - p_{y,1}] K_{c,3}$$

$$\dot{p}_{y,1}' = \begin{cases} \dot{p}_{y,1}'' & (\dot{p}_{y,1}'' > -0.06) \\ -0.06 & (\dot{p}_{y,1}'' \leq -0.06) \end{cases}$$

$$p_{y,1} = \begin{cases} 0.8 & (p_{y,1}' > 0.8) \\ p_{y,1}' & (-0.1 \leq p_{y,1}' \leq 0.8) \\ -0.1 & (p_{y,1}' < -0.1) \end{cases}$$

$$\dot{p}_{y,2}'' = K_{y,2} \left[ (f_{i,y} - \ddot{y}) \left( \frac{\partial \ddot{y}}{\partial p_{y,2}} - \frac{\partial f_{i,y}}{\partial p_{y,2}} \right) + w_y (\dot{\phi}_a - \dot{\phi}) \frac{\partial \dot{\phi}}{\partial p_{y,2}} - b_{y,y} \frac{\partial y}{\partial p_{y,2}} - c_y \dot{y} \frac{\partial \dot{y}}{\partial p_{y,2}} \right]$$

$$\dot{p}_{y,2}' = \begin{cases} 0.1 & (\dot{p}_{y,2}'' > 0.1) \\ \dot{p}_{y,2}'' & (-0.1 \leq \dot{p}_{y,2}'' \leq 0.1) \\ -0.1 & (\dot{p}_{y,2}'' < -0.1) \end{cases}$$

$$p_{y,2} = \begin{cases} 0.01 & (p_{y,2}' > 0.01) \\ p_{y,2}' & (-0.01 \leq p_{y,2}' \leq 0.01) \\ -0.01 & (p_{y,2}' < -0.01) \end{cases}$$

$$\dot{p}_{y,3}'' = K_{y,3} \left[ (f_{i,y} - \ddot{y}) \left( \frac{\partial \ddot{y}}{\partial p_{y,3}} - \frac{\partial f_{i,y}}{\partial p_{y,3}} \right) + w_y (\dot{\phi}_a - \dot{\phi}) \frac{\partial \dot{\phi}}{\partial p_{y,3}} - b_{y,y} \frac{\partial y}{\partial p_{y,3}} - c_y \dot{y} \frac{\partial \dot{y}}{\partial p_{y,3}} \right] + [p_{y,3}'(0) - p_{y,3}] K_{c,4}$$

# APPENDIX

$$\dot{p}'_{y,3} = \begin{cases} \dot{p}''_{y,3} \\ -0.2 \end{cases} \quad \begin{aligned} &(\dot{p}''_{y,3} \geq -0.2) \\ &(\dot{p}''_{y,3} < -0.2) \end{aligned}$$

$$p_{y,3} = \begin{cases} 0.3 \\ p'_{y,3} \\ 0 \end{cases} \quad \begin{aligned} &(p'_{y,3} > 0.3) \\ &(0 \leq p'_{y,3} \leq 0.3) \\ &(p'_{y,3} < 0) \end{aligned}$$

$$\left( \frac{\ddot{\partial y}}{\partial p_{y,1}} \right) = f_{i,y} - d_y \left( \frac{\dot{\partial y}}{\partial p_{y,1}} \right) - e_y \left( \frac{\partial y}{\partial p_{y,1}} \right)$$

$$\left( \frac{\ddot{\partial y}}{\partial p_{y,2}} \right) = p_{y,1} \frac{\partial f_{i,y}}{\partial p_{y,2}} - d_y \left( \frac{\dot{\partial y}}{\partial p_{y,2}} \right) - e_y \left( \frac{\partial y}{\partial p_{y,2}} \right)$$

$$\left( \frac{\ddot{\partial y}}{\partial p_{y,3}} \right) = p_{y,1} \frac{\partial f_{i,y}}{\partial p_{y,3}} - d_y \left( \frac{\dot{\partial y}}{\partial p_{y,3}} \right) - e_y \left( \frac{\partial y}{\partial p_{y,3}} \right)$$

$$\left( \frac{\dot{\partial \phi}}{\partial p_{y,2}} \right) = -f_{i,y} - p_{y,2} \frac{\partial f_{i,y}}{\partial p_{y,2}}$$

$$\left( \frac{\dot{\partial \phi}}{\partial p_{y,3}} \right) = -p_{y,2} \frac{\partial f_{i,y}}{\partial p_{y,3}} + \dot{\phi}_a$$

$$\frac{\partial f_{i,y}}{\partial p_{y,2}} = \left[ f_{s,y} (\cos \phi \sin \theta \sin \psi - \sin \phi \cos \psi) + g (\sin \phi \sin \theta \sin \psi + \cos \phi \cos \psi) \right] \frac{\partial \phi}{\partial p_{y,2}}$$

$$\frac{\partial f_{i,y}}{\partial p_{y,3}} = \left[ f_{s,y} (\cos \phi \sin \theta \sin \psi - \sin \phi \cos \psi) + g (\sin \phi \sin \theta \sin \psi + \cos \phi \cos \psi) \right] \frac{\partial \phi}{\partial p_{y,3}}$$

$$f_{i,y} = S_x f_{s,x} (\cos \theta \sin \psi) + S_y f_{s,y} (\sin \phi \sin \theta \sin \psi + \cos \phi \cos \psi) - g (\cos \phi \sin \theta \sin \psi - \sin \phi \cos \psi)$$

# APPENDIX

Yaw filter equations:

$$\dot{\psi} = p_{\psi}\dot{\psi}_a - e_{\psi}\psi$$

$$\dot{p}_{\psi} = K_{\psi} \left[ (\dot{\psi}_a - \dot{\psi}) \frac{\partial \dot{\psi}}{\partial p_{\psi}} - b_{\psi} \psi \frac{\partial \dot{\psi}}{\partial p_{\psi}} \right] + [p'_{\psi}(0) - p_{\psi}] K_{c,5}$$

$$\dot{p}_{\psi} = \begin{cases} \dot{p}_{\psi}'' & (\dot{p}_{\psi}'' > -0.4) \\ -0.4 & (\dot{p}_{\psi}'' \leq -0.4) \end{cases}$$

$$p_{\psi} = \begin{cases} 1 & (p'_{\psi} > 1) \\ p'_{\psi} & (0 \leq p'_{\psi} \leq 1) \\ 0 & (p'_{\psi} < 0) \end{cases}$$

$$\left( \frac{\partial \dot{\psi}}{\partial p_{\psi}} \right) = \dot{\psi}_a - e_{\psi} \left( \frac{\partial \psi}{\partial p_{\psi}} \right)$$

Heave filter equations:

$$\ddot{z} = p_z \dot{c} - d_z \dot{z} - e_z z$$

$$\dot{p}_z'' = K_z \left[ (\dot{c} - \ddot{z}) \left( \frac{\partial \ddot{z}}{\partial p_z} \right) - b_z z \left( \frac{\partial \dot{z}}{\partial p_z} \right) - c_z \dot{z} \left( \frac{\partial \dot{z}}{\partial p_z} \right) \right] + [p'_z(0) - p_z] K_{c,6}$$

$$\left( \frac{\partial \ddot{z}}{\partial p_z} \right) = \dot{c} - d_z \left( \frac{\partial \dot{z}}{\partial p_z} \right) - e_z \left( \frac{\partial z}{\partial p_z} \right)$$

$$\dot{p}_z' = \begin{cases} \dot{p}_z'' & (\dot{p}_z'' > -1.0) \\ -1.0 & (\dot{p}_z'' \leq -1.0) \end{cases}$$

$$p_z = \begin{cases} 1.0 & (p'_z > 1.0) \\ p'_z & (0 \leq p'_z \leq 1.0) \\ 0 & (p'_z < 0) \end{cases}$$

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TABLE I.- PERFORMANCE LIMITS FOR SINGLE-DEGREE-OF-FREEDOM  
OPERATION WITH A NEUTRAL POINT OF 0.6161 m (2.02 ft)

Degrees of freedom	Performance limits		
	Position	Velocity	Acceleration
Longitudinal, x	Forward 1.245 m Aft 1.219 m	$\pm 0.610$ m/sec	$\pm 0.6g$
Lateral, y	Left 1.219 m Right 1.219 m	$\pm 0.610$ m/sec	$\pm 0.6g$
Vertical, z	Up 0.991 m Down 0.762 m	$\pm 0.610$ m/sec	$\pm 0.8g$
Yaw, $\psi$	$\pm 32^\circ$	$\pm 15^\circ/\text{sec}$	$\pm 50^\circ/\text{sec}^2$
Pitch, $\theta$	$\pm 30^\circ$ $-20^\circ$	$\pm 15^\circ/\text{sec}$	$\pm 50^\circ/\text{sec}^2$
Roll, $\phi$	$\pm 22^\circ$	$\pm 15^\circ/\text{sec}$	$\pm 50^\circ/\text{sec}^2$

TABLE II.- NONLINEAR WASHOUT PARAMETER VALUES

Variable*	Value in SI Units	Program value in U.S. Units	Variable*	Value in SI Units	Program value in U.S. Units
$b\psi$ , per $\text{sec}^2$	1.0	1.0	$e_y$ , per $\text{sec}^2$	0.81	0.81
$e\psi$ , per $\text{sec}$	.3	.3	$K_{y,1}$ , $\text{sec}^3/\text{m}^2$ ( $\text{sec}^3/\text{ft}^2$ )	.51668	.048
$K\psi$ , $\text{sec}$	100	100	$K_{y,2}$ , $\text{sec}^5/\text{m}^4$ ( $\text{sec}^5/\text{ft}^4$ )	0	0
$W_x$ , $\text{m}^2/\text{sec}^2$ ( $\text{ft}^2/\text{sec}^2$ )	61.686	664	$K_{y,3}$ , $\text{sec}^3/\text{m}^2$ ( $\text{sec}^3/\text{ft}^2$ )	.2691	.025
$b_x$ , per $\text{sec}^4$	.1	.1	$b_z$ , per $\text{sec}^4$	.5	.5
$c_x$ , per $\text{sec}^2$	2	2	$c_z$ , per $\text{sec}^2$	.1	.1
$d_x$ , per $\text{sec}$	1.2727	1.2727	$d_z$ , per $\text{sec}$	1.2727	1.2727
$e_x$ , per $\text{sec}^2$	.81	.81	$e_z$ , per $\text{sec}^2$	.81	.81
$K_{x,1}$ , $\text{sec}^3/\text{m}^2$ ( $\text{sec}^3/\text{ft}^2$ )	.51668	.048	$K_z$ , $\text{sec}^3/\text{m}^2$ ( $\text{sec}^3/\text{ft}^2$ )	10.764	1.0
$K_{x,2}$ , $\text{sec}^5/\text{m}^4$ ( $\text{sec}^5/\text{ft}^4$ )	0	0	$K_{c,1}$ , per $\text{sec}$	.05	.05
$K_{x,3}$ , $\text{sec}^3/\text{m}^2$ ( $\text{sec}^3/\text{ft}^2$ )	.75348	.07	$K_{c,2}$ , per $\text{sec}$	.5	.5
$W_y$ , $\text{m}^2/\text{sec}^2$ ( $\text{ft}^2/\text{sec}^2$ )	.00929	.1	$K_{c,3}$ , per $\text{sec}$	.05	.05
$b_y$ , per $\text{sec}^4$	.1	.1	$K_{c,4}$ , per $\text{sec}$	1.5	1.5
$c_y$ , per $\text{sec}^2$	2.0	2.0	$K_{c,5}$ , per $\text{sec}$	.1	.1
$d_y$ , per $\text{sec}$	1.2727	1.2727	$K_{c,6}$ , per $\text{sec}$	.05	.05

\*Where two sets of units are given, the first is the SI Unit and the second is the U.S. Unit.

TABLE III.- ANALYSES OF VARIANCE RESULTS

Factors	Degrees of freedom	Root-mean-square measures								Altitude	Primary task	Secondary task
		Tail-rotor pedal		Cyclic pitch		Cyclic roll		Collective				
		Position	Rate	Position	Rate	Position	Rate	Position	Rate			
Replicates	4	*	**	---	*	---	---	---	---	---	---	**
Days, A	3	**	**	**	**	**	**	**	**	**	**	**
Pilots, B	3	**	**	**	**	**	**	**	**	**	**	**
Motion, C	1	**↓	**↓	**↓	**↓	---	---	**↓	**↑↓	**↑	---	---
AB	9	**	**	**	**	**	**	**	**	**	**	**
AC	3	---	---	---	---	---	---	---	---	---	---	*
BC	3	**	**	**	---	**	**	**	**	---	---	---
ABC	9	**	---	---	---	---	---	*	*	---	---	---
Error	124											
Total	159											

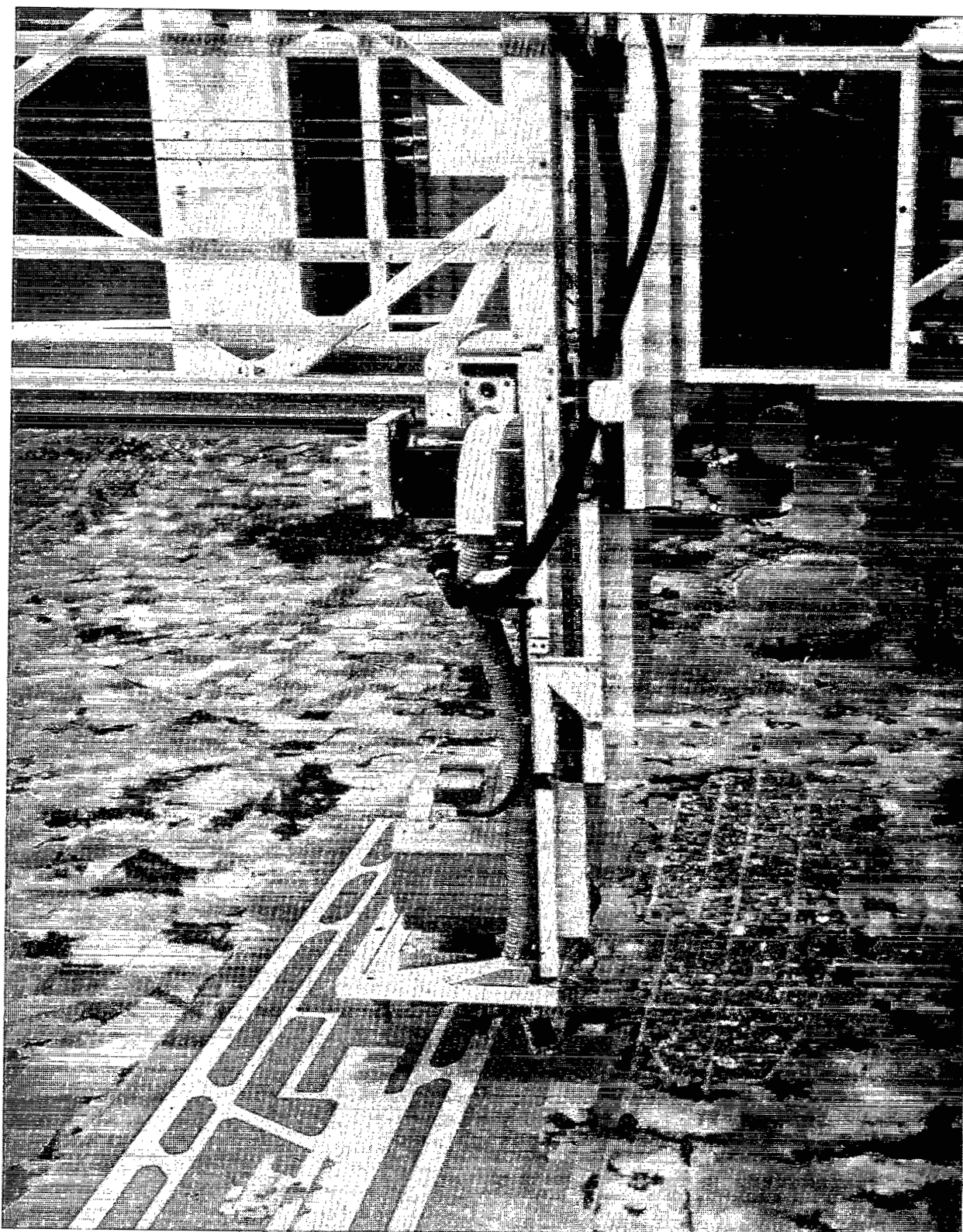
\*5-percent level significance.

\*\*1-percent level significance.

↓ Measures are lower with motion than with fixed base.

↑ Measures are higher with motion than with fixed base.

↑↓ Varies with pilot.



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Figure 1.- The visual landing display system.

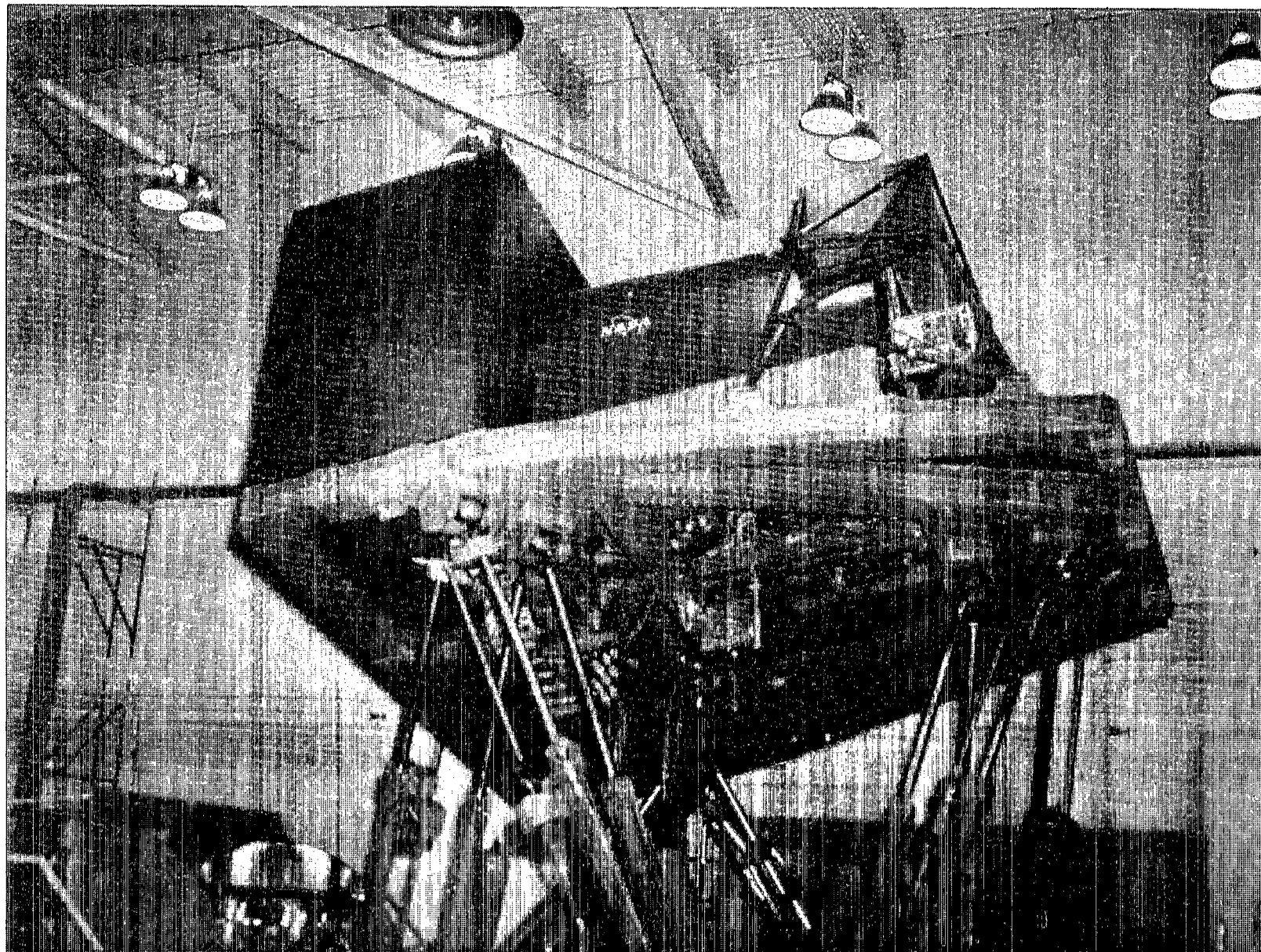


Figure 2.- Langley six-degree-of-freedom motion simulator.

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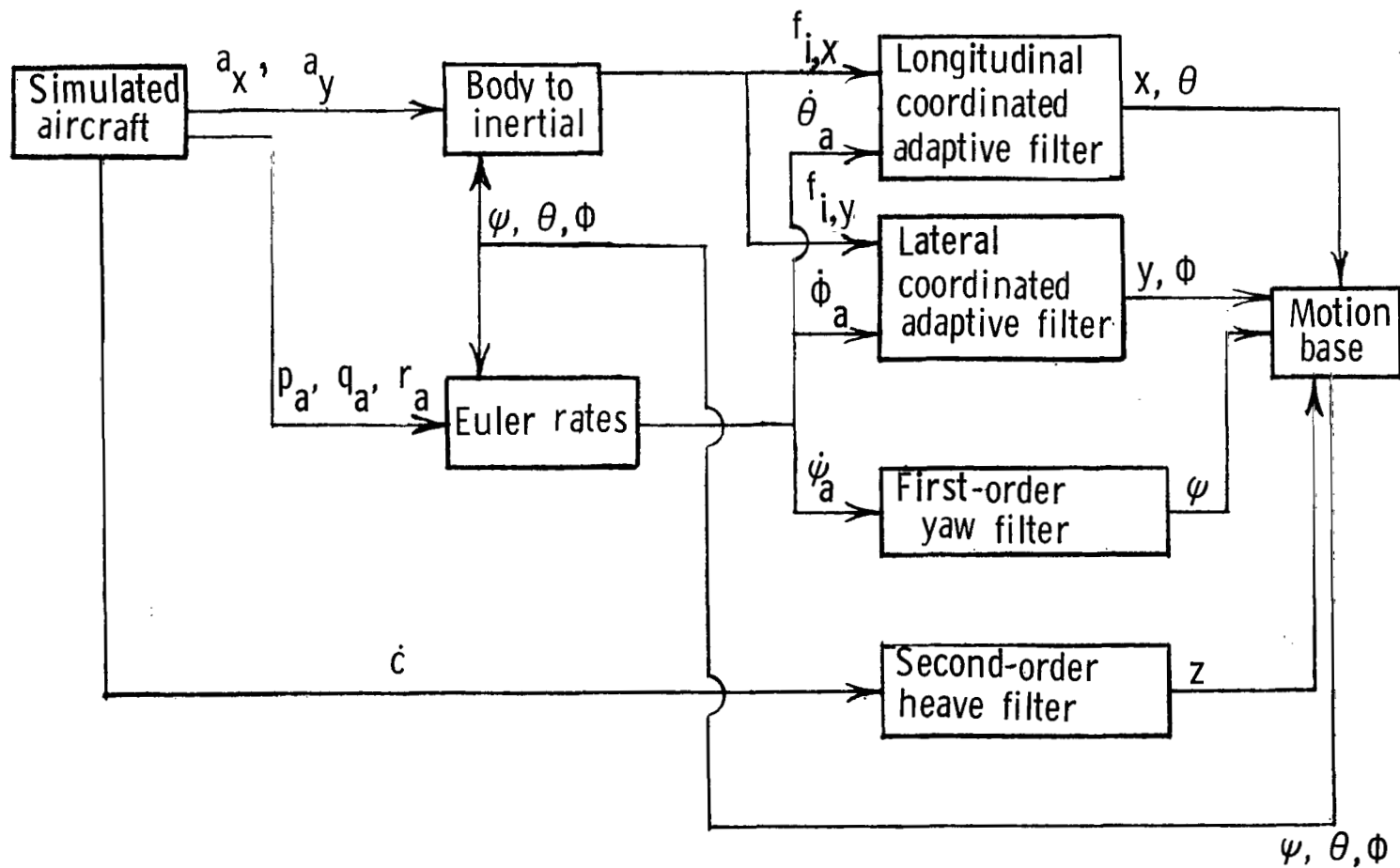
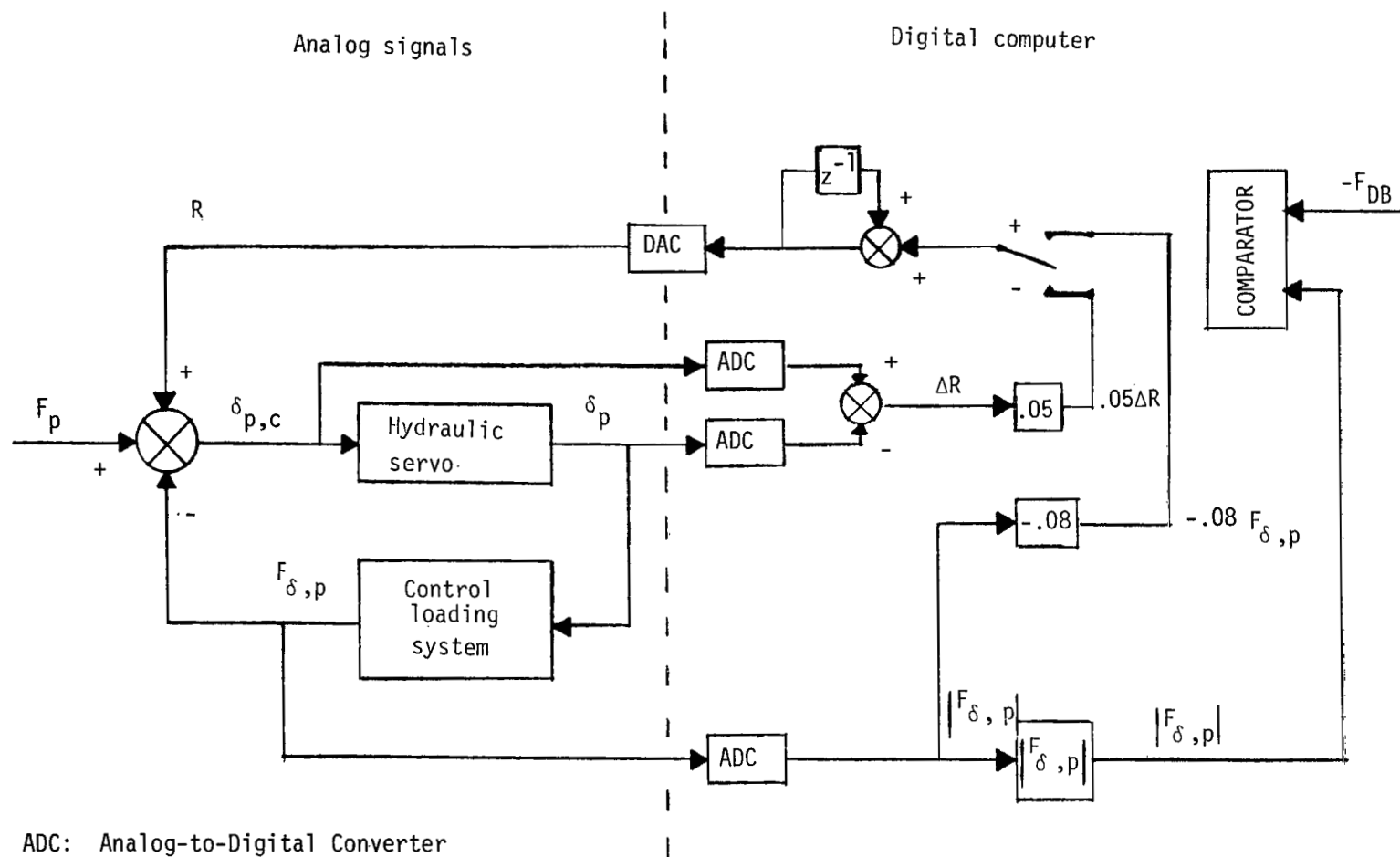


Figure 3.- Coordinated adaptive washout.



ADC: Analog-to-Digital Converter

DAC: Digital-to-Analog Converter

$z^{-1}$ : one iteration delay

Figure 4.- Free-floating rudder pedal circuit.

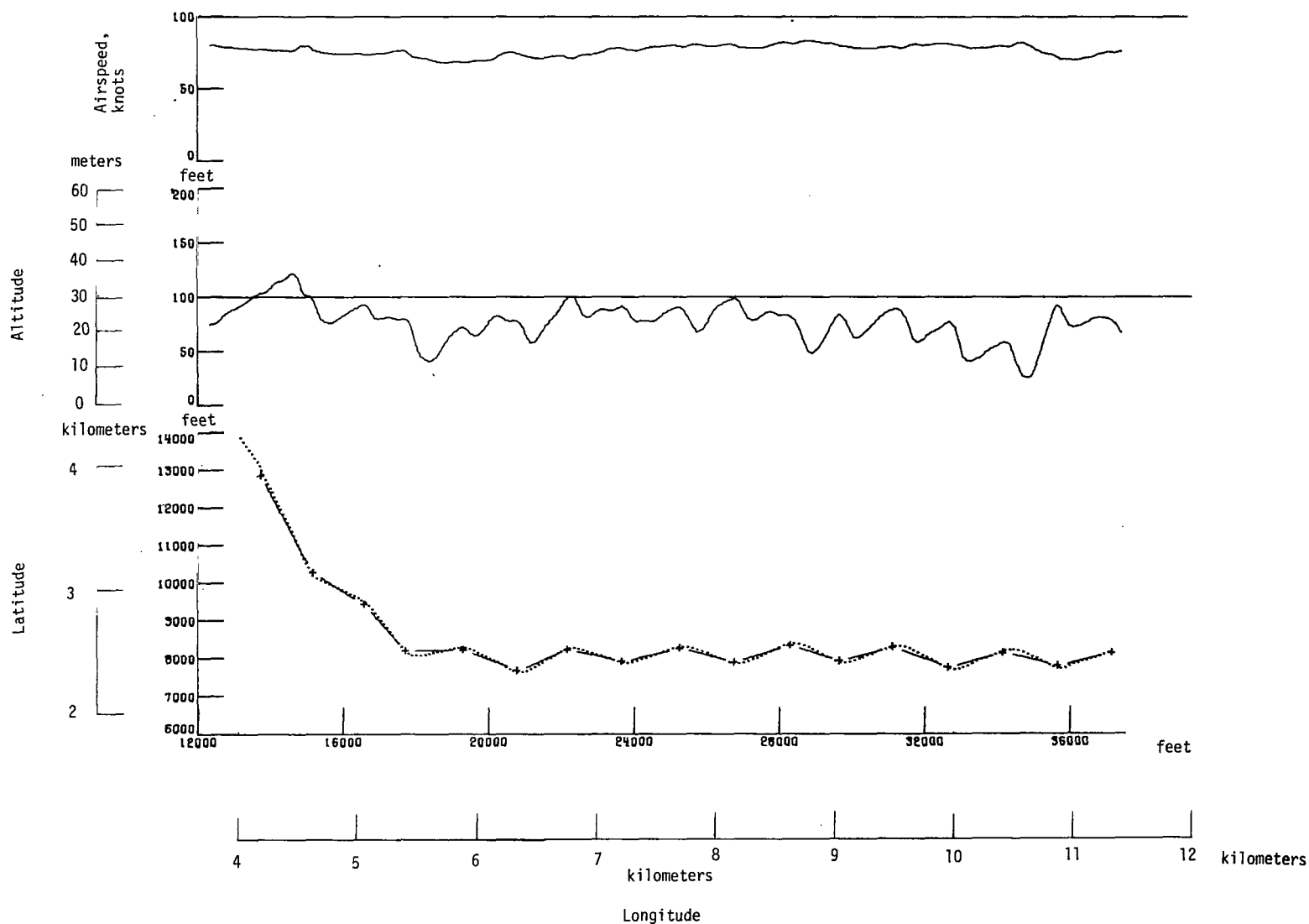


Figure 5.- A typical ground track.

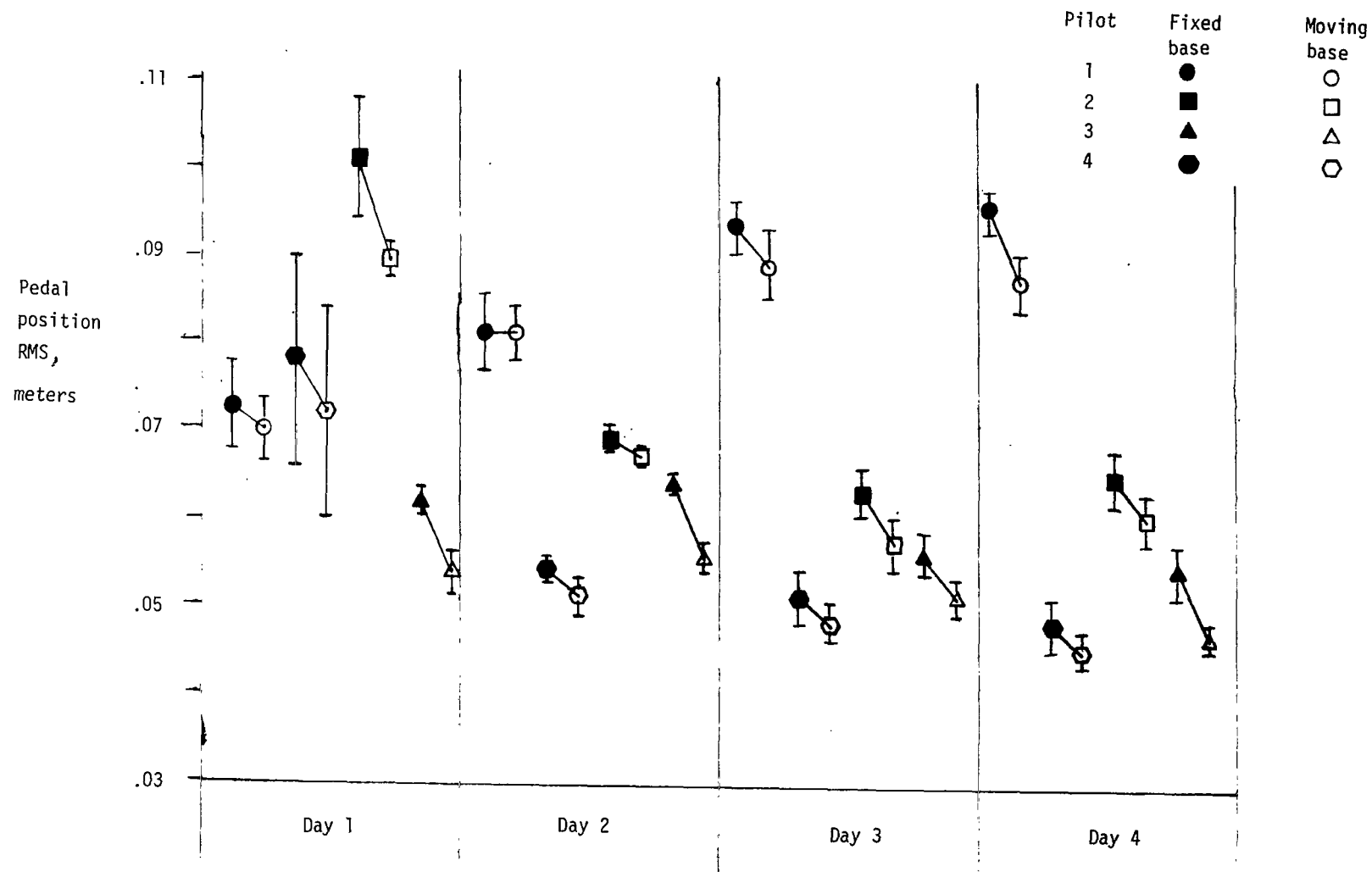


Figure 6.- Pedal position as a function of day, pilot, and motion conditions.

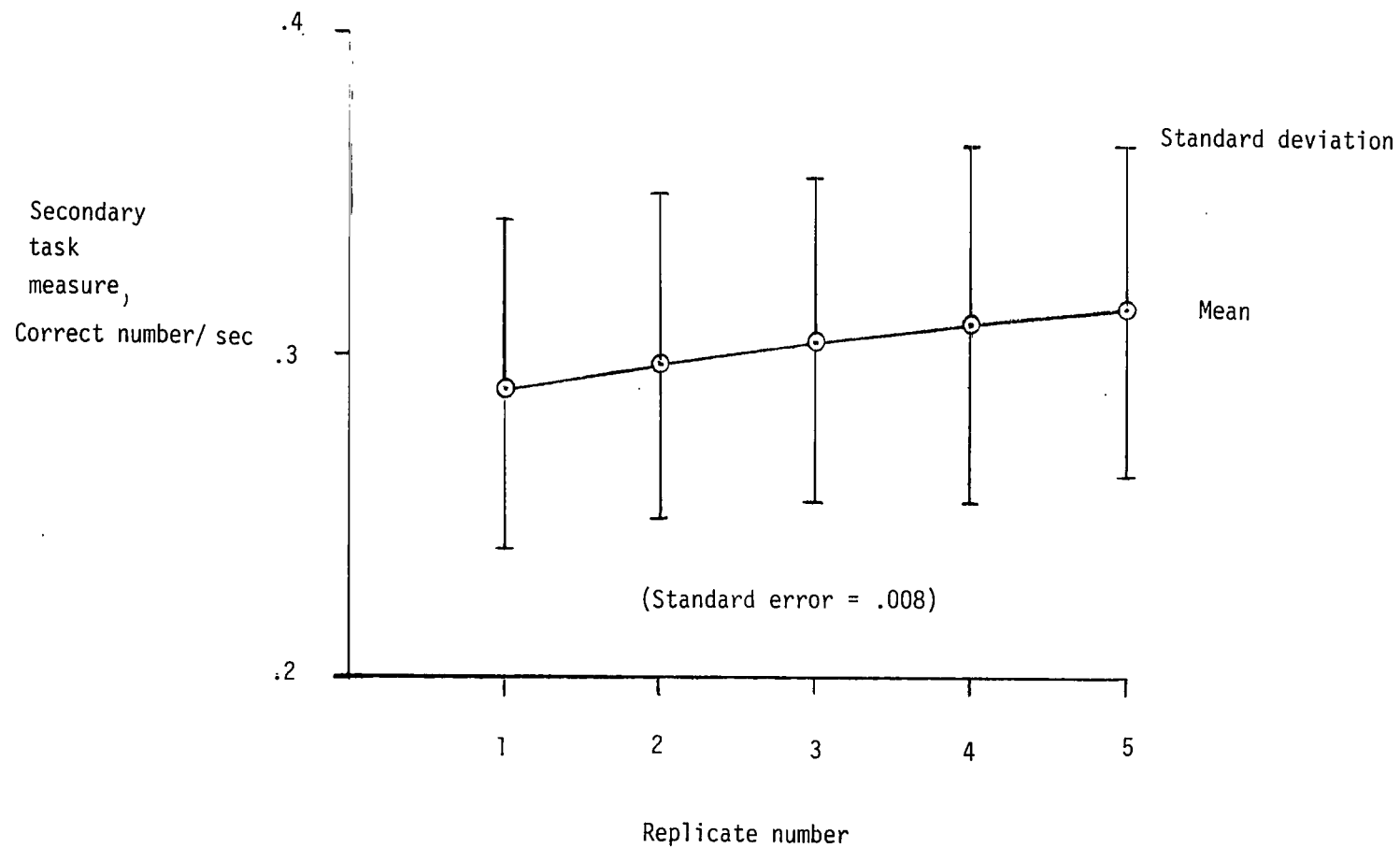


Figure 7.- Secondary task learning curve during replication.

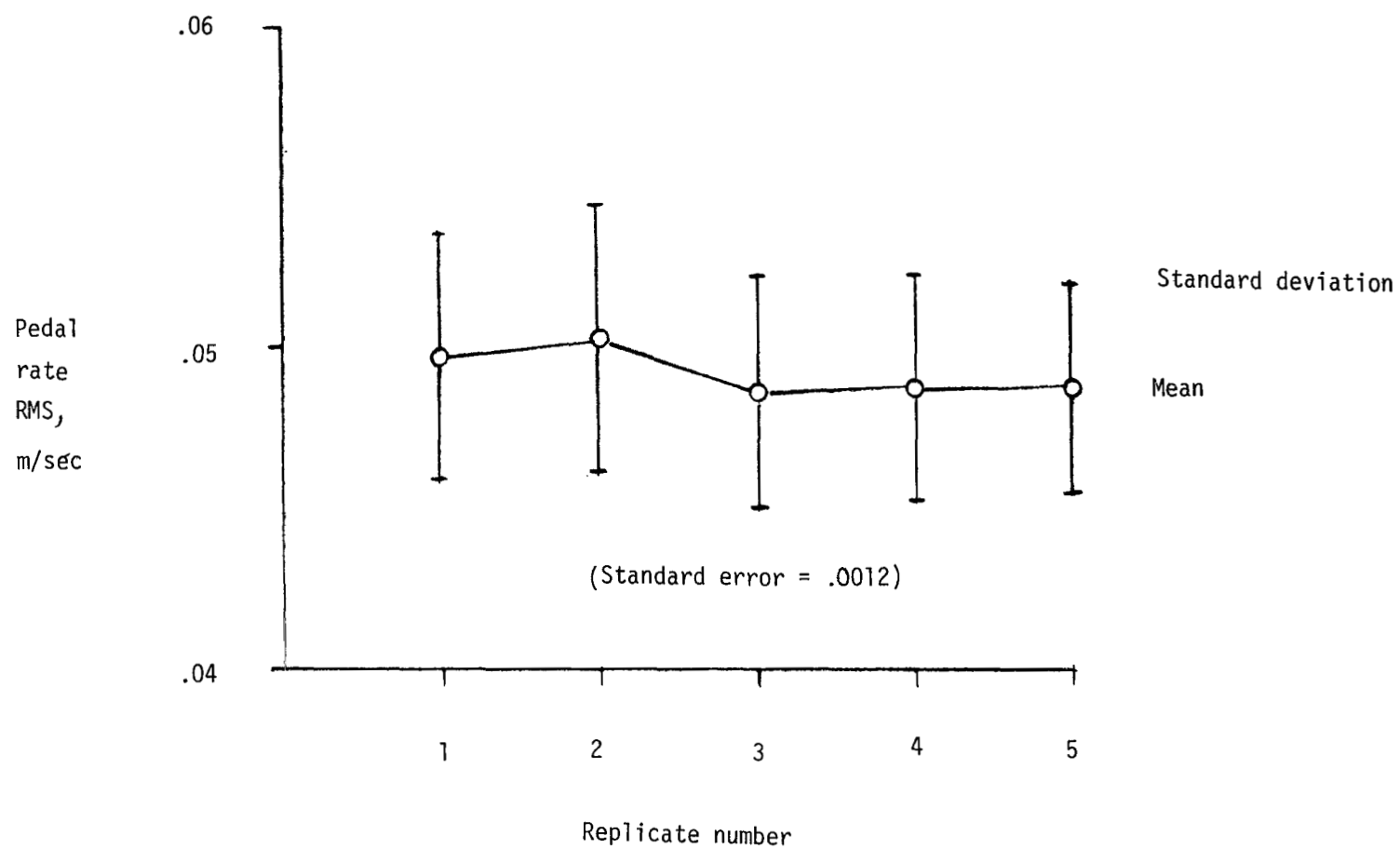


Figure 8.- Pedal rate RMS as a function of replication.

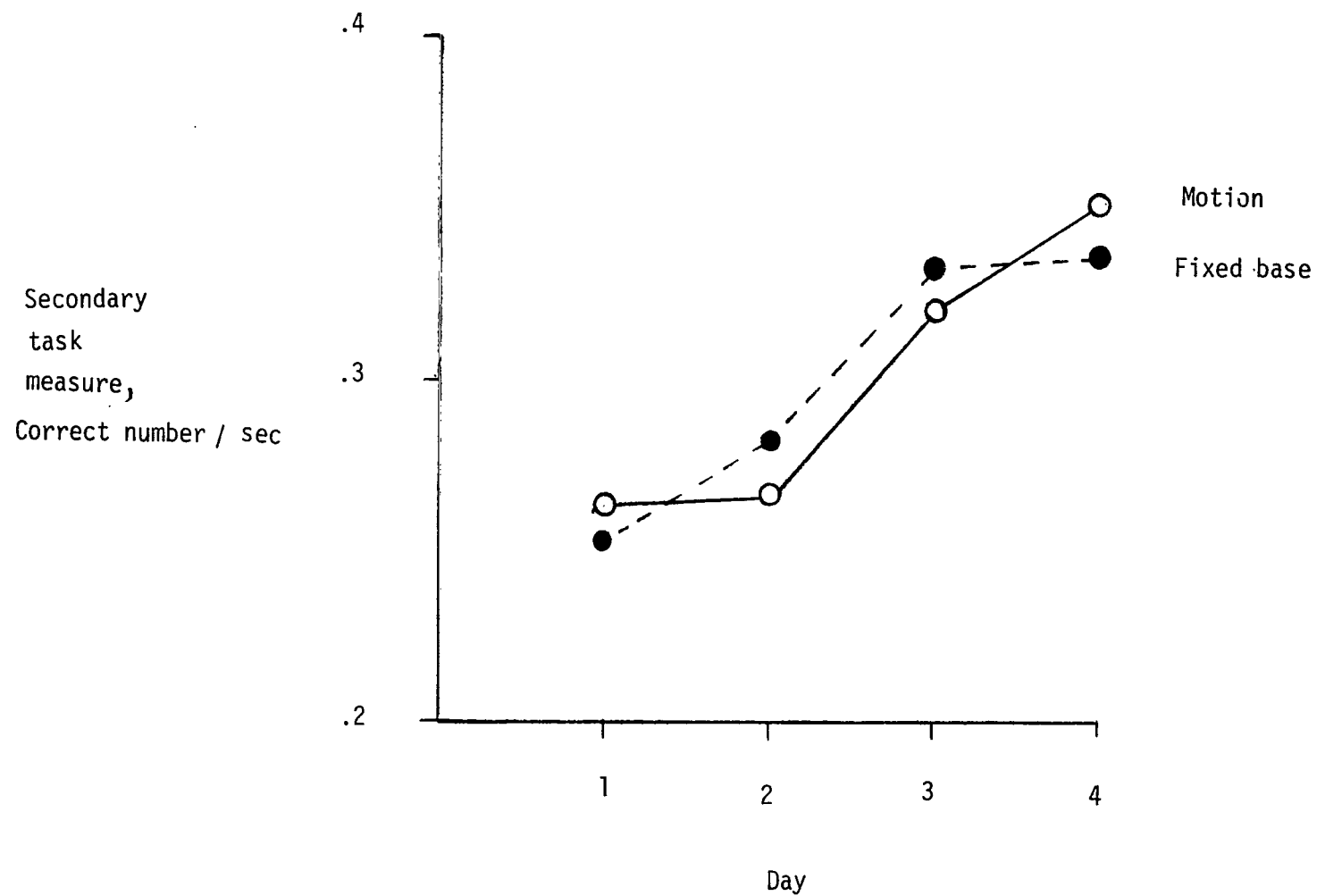


Figure 9.- Days-motion interaction for the secondary task.

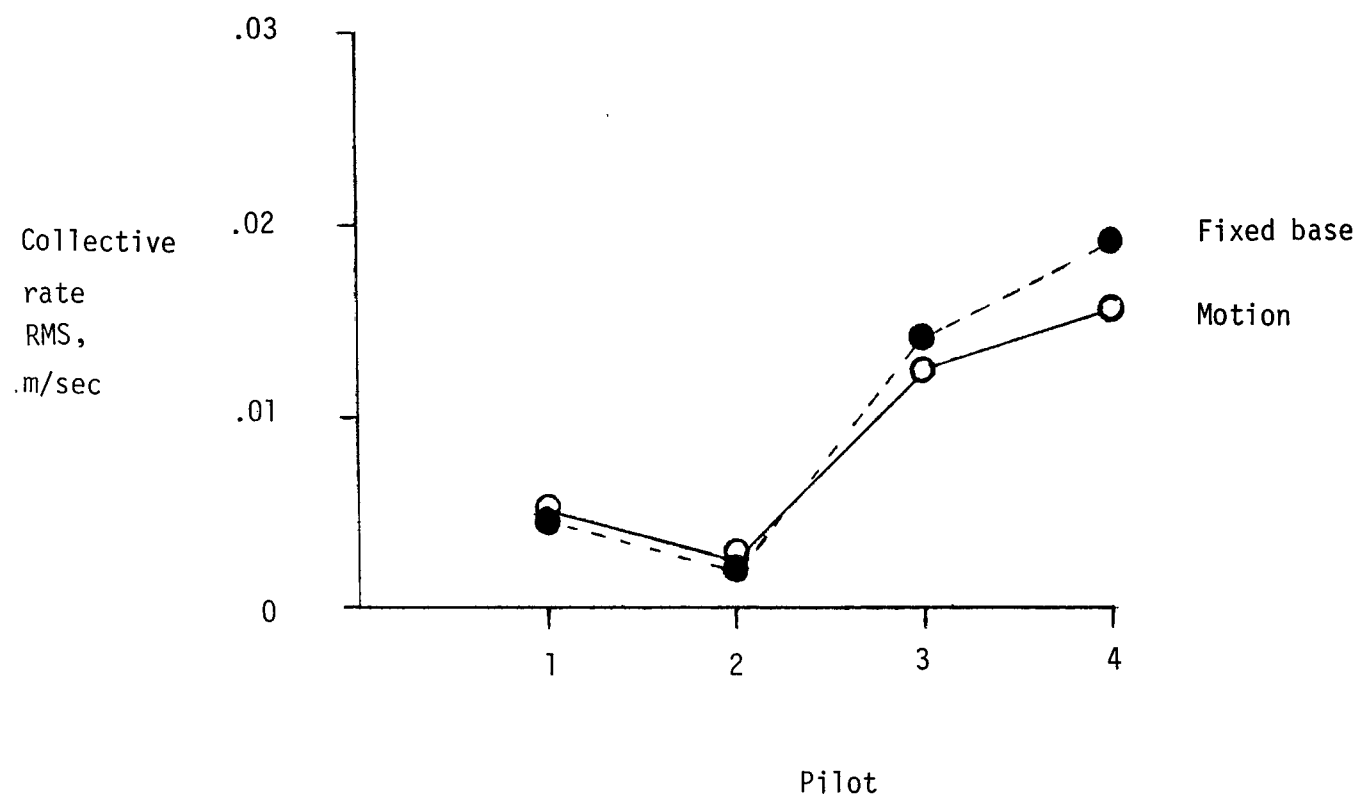


Figure 10.- Pilots-motion interaction for collective rate measure.

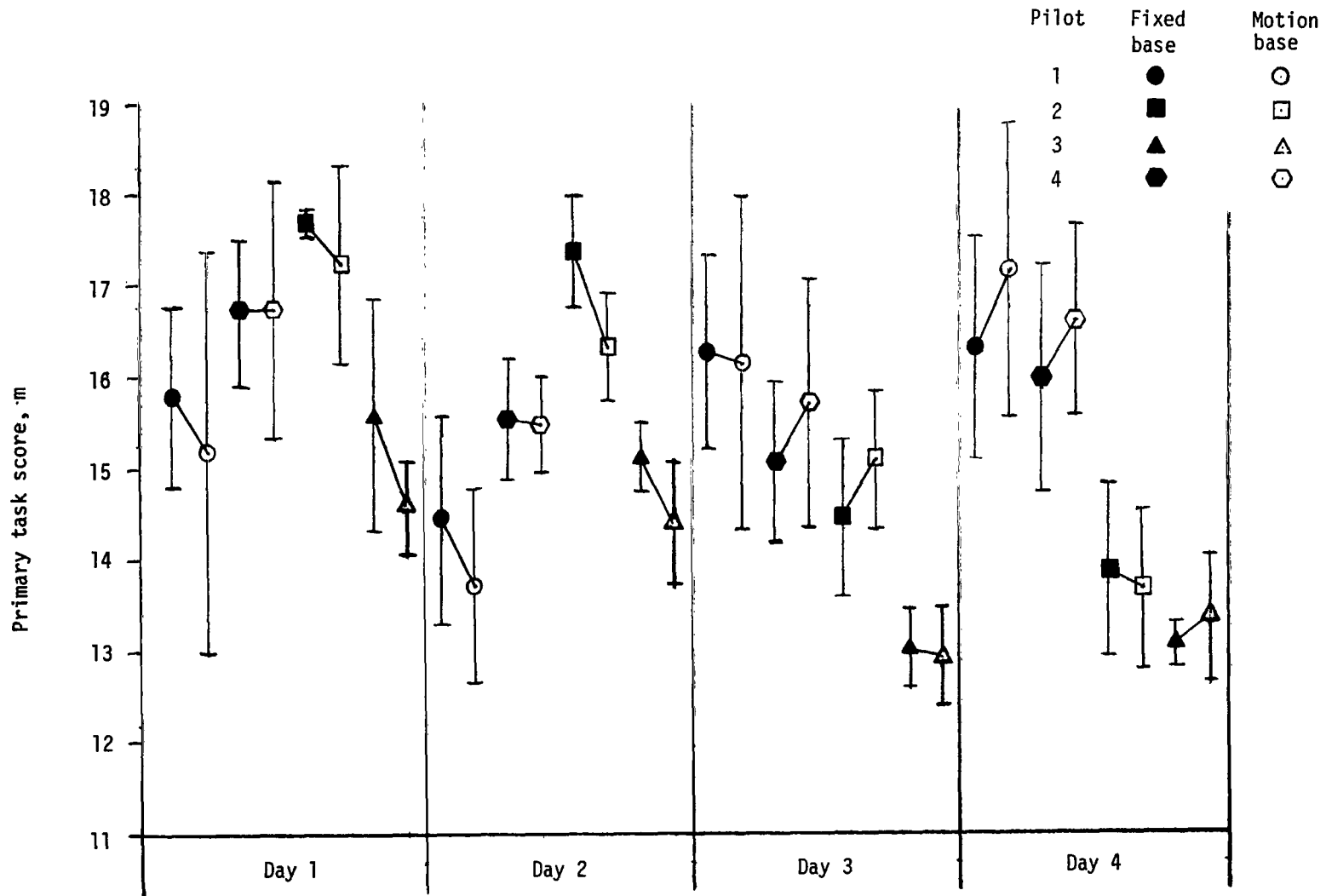


Figure 11.- Primary task measure as a function of day, pilot, and motion conditions.



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